Local Measurement of Fuel Energy Deposition and Heat Transfer Environmental Fuel Lifetime Using Controlled Calimetry

Phase 1 (July 1, 1999-June 30. 2000)

by

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Program Objectives

The goal of this two year program is 'to develop an in-core sensor that is capable of directly measuring the parameters most closely related to the basic reactor safety issues, fuel melt and core coolability and to provide the basis for incorporation of this in-situ sensor In the fuel in next generation reactors". The specific objectives for the first year (Phase 1) were**:**

(a) to develop a comprehensive model of the sensor for use in developing experimental methods and comparison with experimental measurements.

(b) to design, construct and test an-in-reactor test facility that provides a synergistic neutronic/high temperature environment comparable to the environment expected in next generation reactor designs.

(c) to design, construct and test sensor electronics.

(d) to fabricate sensor prototypes.

Summary of accomplishments

A comprehensive model of the sensor has been developed and has been used to assist in the design of the next generation sensors and sensor control electronics. The in-reactor test facility has been designed, and construction and preliminary testing will be complete by June 30, 2000. A local flux oscillator was included in the facility. Although the addition of a flux oscillator required unplanned effort, we felt it was necessary since we had determined from previous work that the use of noise analysis was inadequate to properly characterize the dynamic properties of the CTPS. The sensor feedback controller has been designed, and construction and preliminary testing will be completed by June 30, 2000. Fabrication of prototype sensors will begin in July. Prototypes, fabricated without fissile material, are expected to be ready for testing by August 1 and prototypes with fissile material, which will be fabricated after the sensor feedback controller testing is complete, are expected to be ready for testing by October 1. We believe this delay in the experimental program will be compensated by the improvements in the test facility, which will facilitate both experimental measurements and data analysis.

The following sections provide a more detailed discussion of progress on each of the four objectives.

(a) Numerical model of the CTPS instrument

We have developed a numerical model of the sensor and associated electronics and have validated it with experimental data. The model has four major components: a physical sensor model, a feedback controller model, and a model of the sensor neutronics and the environment surrounding the sensor. A transient r-z heat conduction model that allows for multiple materials and thermal contact resistances represents the physical sensor. Thermal boundary conditions are represented by convection to the environment and a separate transient electrical lead conduction model. This model predicts transient temperature distribution within the sensor and heated element resistance given an input distribution of power deposition. Power deposited by neutrons, decay beta particles, photons and resistive dissipation is calculated in each node of the thermal model. Neutron and photon deposition are calculated from straightforward interaction models, as self-shielding has been demonstrated to be minimal in these small sensors. Decay power is estimated using an empirical algorithm based on a stored history of sensor exposure. The resulting power deposition has been compared to detailed MCNP calculations. The feedback controller model has two parts: an unbalanced Wheatstone bridge model that generates an error signal from the sensor resistance, and a controller transfer function that converts the error into a control signal and drives the bridge with the resulting output. The transfer function is currently that of a proportional controller, but other transfer functions can be easily incorporated. This capability allows for numerical testing of dynamic compensation algorithms. Finally, the sensor environment is represented by a monoenergetic flux of thermal neutrons and photons, by the thermal convection fluid properties, and by the electrical lead sink temperature.

Data on sensor sensitivity, bandwidth and response to thermal environment obtained from first-generation sensor prototypes have been compared to the predictions of this numerical model. The magnitude of sensor sensitivity was well predicted, as was the linear response of the sensor to changes in environmental heat rejection. Sensor bandwidth and its associated sensitivities were reasonably predicted even though the experimental measurement of bandwidth was problematic. The sensor dynamics were found to be characterized by several time scales, and instrument response to neutrons and photons was noted to be quite different. Heat transfer process internal to the sensor were also noted to be important during measurement transients if energy deposition is not uniform or if local thermal leakage paths exist. This partial verification of the numerical model has given substantial insight to the sensor dynamics and has proven to be a critical component in the development of the next generation of sensor prototypes.

To facilitate the task of second-generation sensor and controller design, we have also developed a simple 2-node model of the sensor and controller. This model can be used to rapidly study parameter changes that do not significantly affect the detailed temperature distribution in the sensor. In addition this model could serve as a transfer function model for a sophisticated optimizing controller in the final instrument.

(b) In-reactor test facility

We have designed an in-reactor test facility to synergistically evaluate the static and dynamic performance of the prototype CTPS in environmental and neutronic conditions similar to those expected in a high-temperature gas reactor. This facility has been designed to:

- heat the sensors up to 800 C.
- provide a gas flow velocity of 350 liters per second in a closed cooling loop.

- provide the maximum neutron flux level as achievable in the OSU Research Reactor.
- sinusoidally modulate by approximately five percent the neutron flux from one Hz through 100 Hz. (See separate discussion of the neutron flux oscillator.)
- independently monitor the neutron flux, the gamma flux, and the temperature at selected locations.
- shield parts and components that may become excessively radioactive.

The LVEC dry-tube was chosen to house the CTPS test facility. It is an aluminum dry tube with a 9.5" inner diameter that is secured next to the reactor. The LVEC facility was selected since it has sufficient space to house both the neutron-flux oscillator and the high-temperature facility and is located in a high neutron flux. An MCNP simulation predicted a neutron flux of ~ $1x10^{12}$ nv at the position of the sensors.

There were a number of design constraints that were considered in the location and design of the in-reactor test facility in the LVEC. The high-temperature facility and flux oscillator must be positioned near the bottom of a 17' tube. This means that a support structures for the coolant tubes, wire conduits, high-temperature facility, neutron flux oscillator, and oscillator drive shaft must be an integral part of the design. This support structure must be designed in sections that can be disassembled since there is limited space between the reactor pool and the building's ceiling, and the structure must prevent the drive shaft for the oscillator from moving radially (whipping) within the tube. The material used in the facility must also be selected to minimize neutron activation. This requires that the structure is constructed from materials such as aluminum and the motor for the oscillator must be located at the top of the tube where the neutron flux is relatively low. Where possible, components that can activate should be shielded. In addition, the facility must be designed so that the sensors can be inserted and removed from the coolant loop without removing the entire assembly from the LVEC. The parts of the facility that will become activated must be designed so that they can be quickly removed if they need to be replaced, to minimize personnel exposure. Finally, high temperatures must be confined to the high-temperature facility. The aluminum parts and polyethylene neutron shielding must be located such that the maximum temperature is below their melting points. Finally the temperature in the LVEC must be limited so that reactor pool water near the tube is less than 100 C.

The support structure is an aluminum skeleton, which has three six foot sections consisting of aluminum plates attached to a threaded aluminum rod. All of the components of the test facility are attached to this support structure. The bottom section houses the oscillator and the high-temperature facility as well as neutron shielding to prevent excessive neutron activation of the bearings. The middle section holds wire conduits, cooling-loop pipes and the oscillator shaft. The top section holds pipes, conduits, shaft, and the oscillator motor. Couplings are used to connect the pipe sections and sleeves with setscrews are used to connect the aluminum oscillator drive shaft sections. The weight of the oscillator is supported by taper-roller bearings attached to the bottom assembly section and the cooling-loop tubes support the high-temperature facility.

A fission chamber will be used to monitor the neutron flux and an ion chamber will monitor the gamma flux. These sensors will be located as close as possible to the prototype CTPS without being in the high-temperature facility. (They are not designed for high temperatures.) Type-K thermocouples will monitor temperature at a number of locations within and outside the high-temperature facility.

The high-temperature facility contains a 3 kW alumina and nichrome element to heat the coolant-loop gas. The heater sits in a graphite cylinder, which is housed in a quartz bottle to contain the airflow. This assembly sits atop a perforated aluminum plate that creates a pressure drop to develop evenly distributed flow into the heater, which reduces premature burnout of the heating element. A blower outside of the LVEC provides the airflow and the loop is completed with one inch aluminum pipe. This pipe is large enough so that sensors can be installed without a significant pressure drop over its two 17' lengths. A laminar flow meter will be used to monitor flow rate and a type-k thermocouple will be used to measure the temperature at the exit of the heater.

Neutron Flux Oscillator

In a previous study the use of noise analysis was shown to be insufficient for determining the frequency response of test sensors. As a consequence we decided to include a local neutron flux oscillator in the in-reactor test facility. The design of the oscillator had to consider available space and global reactivity. It must be reasonably compact to allow enough space for the high-temperature facility and since the sensors need to be tested at full reactor power, to comply with reactor technical specifications the oscillator must modulate the neutron flux near the sensors without changing the reactor power.

The oscillator is comprised of a cylindrical body of a moderator that has an absorber on one side and spins along its axis, connected by a shaft to a motor. This gives a sinusoidal flux oscillation. Graphite is used as the body since it retains physical integrity at high neutron fluence. Cadmium was chosen as the absorber since it can be easily shaped. The oscillator is positioned on the far side of the sensors from the reactor to maximize the flux a t the sensor location.

An analytical and experimental assessment of this design was completed to evaluate whether it would meet the performance requirements. MCNP was used to model the use of both polyethylene and graphite as the body. Both gave a five to seven per cent change in flux at the sensor position. Next a mock-up was tested at low reactor power in the LVEC. This test used a Teflon cylinder (similar to polyethylene) with cadmium on one side suspended at the correct height, and a fission chamber in place of the CTPS. The fission chamber response was recorded with the cadmium facing towards and away from it. A flux difference of approximately five per cent was measured, and no change in reactor power was observed.

(c)Sensor feedback controller

The sensor feedback controller has been designed to perform three functions: control the sensors in a constant-temperature manner, perform algorithm(s) to test sensor dynamics and record all the signals used as baselines for comparisons (neutron flux, gamma flux, ambient temperature.).

A study was completed to compare a stand-alone digital controller with a computer-based controller in order to determine which one better meets these requirements. The specific requirements important to the sensor feedback controller include sampling rate

(2000 samples per second per channel); number of channels (Four analog in and two analog out for control), and resolution (16-bit), number crunching speed and capability to run a variety of control algorithms.

A computer-based controller was selected and two computers running Windows NT with National Instruments data-acquisition cards and analog outputs have been purchased and tested. One computer will control the sensors, and the other will stream data to disk. The input boards for these computers sample eight differential channels at 333, 000 per second.

A custom system was designed to interface the sensors with the computers. This system provides the voltage dividers to sensor signals and the power gain necessary for operating the sensors. The design o is complete, and a local company that specializes in fabrication of advanced electronic systems was contracted to do the detailed schematic, and circuit board layout, fabrication and assembly.

By the end of June we expect the sensor feedback controller will be completed and tested. The test will use a PID control algorithm to maintain a “dummy” sensor at constant temperature. The algorithms to estimate external temperature and heat transfer will be incorporated following comparison of the two algorithms that have been developed.

Sensor dynamic response algorithm

Two algorithms to evaluate environmental heat transfer coefficient and bulk coolant temperature from sensor dynamic response data have been developed and are currently being tested. Initial data for testing these thermal compensation algorithms are being taken from a commercial resistance temperature detector (RTD), a device physically similar to our sensor. To use this device, we first quantified its internal thermal resistance. This was accomplished by using external power to heat the RTD in a water tunnel while simultaneously measuring the active platinum wire and surrounding coolant temperatures. The low external convection resistance allowed a low-uncertainty evaluation of internal resistance. The RTD was then subject to input power step changes while the sensor was placed in environments of differing convection coefficient and bulk temperature. These data are being analyzed to find the sensor convection coefficient and the coolant temperature using a least-squares algorithm as well as a more sophisticated probabilistic technique for model-based parameter and state estimation being developed by Professor Tunc Aldemir with the support of a DOE NEER grant. We have completed a preliminary evaluation of both methods. Further evaluation will continue with more realistic data (e.g. various levels of noise. This evaluation will be competed s by the end of June 2000. The algorithm that gives the best performance based on speed of convergence and robustness in the presence of various levels of noise will be incorporated into the sensor feedback controller by August 1, 2000.

(d) Sensor prototype development

The numerical parameter study necessary to optimize performance of the next generation of prototypes is substantially complete. . Four basic configurations have been studied to evaluate linearity and bandwidth.

The results from the first-generation sensor prototypes indicated that the relative response from fission and gamma deposition did not exhibit proportional sensitivity. This was hypothesized to result from using segregated fissile and insulator components in the sensor. We have modeled a sensor design with uniform fissile content and a centralized heater element, and also a design with uniform fissile content and a heated element distributed over the radius of the sensor material. Results from this study indicate the importance of proper control of temperature distribution. A sensor design in which the temperature distribution is similar given all-nuclear or all-electrical heating has better power proportionality and also exhibits improved bandwidth. This goal is difficult to achieve with a sensor configuration like that used for the first-generation prototypes. Uniform sensor fissile content typically means using a nuclear fuel material. These fuels all have good thermal conductivity, which reduces sensor temperature differential. A decrease in temperature difference has been found to adversely affect bandwidth and to increase sensitivity to environmental temperature variations. High-void ceramic fuel material could provide some improvement in temperature differential; however, fabrication of a distributed-heater sensor using a porous ceramic appears unfeasible.

One approach to increasing bandwidth is a reduction in the physical size of the sensor. A third design has been modeled to evaluate the effect of using a smaller overall sensor radius. One might expect that the reduced radius would result in reduced sensor temperature difference also, but delta-T in fact increases with volumetric heat generation if the total sensor power dissipation is maintained while radius is decreased. In addition, the uniformity of nuclear vs. electrical temperature distribution improves as size is decreased. Overall, a significant increase in bandwidth is predicted when sensor radius is decreased when compared to the first configuration discussed. Gains from this design may be limited by sensor surface heat flux, as boiling on the sensor surface is not acceptable. Also, increased heat flux at the surface means a larger film temperature drop, suggesting that reducing the radius of a uniform sensor may again result in increased sensitivity to the sensor environment.

The fourth design follows from the first three studies. In this design a fuel/heater kernel of small radius is thermally connected from the surrounding environment by thin metal axial supports, while a very low density and thermal conductivity ceramic annular insulator limits heat transfer in the radial direction. This design exhibits a relatively uniform temperature distribution in the small kernel, with virtually all of the heat flux and temperature gradient along the axial supports. These supports have high thermal conductivity but low volume, so gamma heating is minimized while still allowing a high sensor temperature difference. All of these features have been demonstrated to contribute to improved bandwidth, to providing a more proportionate neutron/gamma flux response and to minimizing the effect of the sensor environment. Practically, thermal contact resistances will also be better controlled by this design.

The sensor bandwidth is predicted to be between one and 10 Hz substantially greater than observed in the first-generation prototypes. Thermal conductivity, density, temperature differential, and controller gain will be studied to determine the optimal materials and settings for use in the prototype instrument.

Fabrication of prototype sensors will begin by July 1, 2000. Many of the materials for these prototypes have been procured, while others will be procured once the parameter study is complete. Initial prototypes, fabricated without fissile material, are expected to be completed in July. These sensors will be used to test the controller in a constant-temperature mode and also to test the sensor dynamic measurements of convection heat transfer and environmental temperature. This testing may result in changes to the prototype design. Fissile prototypes will be fabricated after the controller testing is complete. We expect these prototypes will be ready to test by September 30, 2000.